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Microgrids research: A review of experimental microgrids and test systems

N.W.A. Lidula *, A.D. Rajapakse [1]

Department of Electrical and Computer Engineering, 75A Chancellor's Circle, University of Manitoba, Winnipeg, Manitoba R3T 5V6, Canada

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ABSTRACT

A microgrid is particularly a portion of the power distribution system that comprises distributed generation, energy storage and loads. To be capable of operating in parallel to the grid, as an autonomous power island and in transition modes, microgrids must be robust in controlling the local voltage and frequency, and protecting the network and equipment connected to the microgrid. It also needs to facilitate demand side management and resynchronization. This paper presents a review of existing microgrid test networks around the world (North America, Europe and Asia) and some significantly different microgrid simulation networks present in the literature. Paper is focused on the test systems and available microgrid control options. A summary table comparing and contrasting the existing test systems is presented. The paper is concluded highlighting the worthy findings and possible areas of research that would enhance practical use of microgrid facilities.

Contents

* Corresponding author. Tel.: +1 480 1403; fax: +1 204 474 7522.
E-mail addresses: lidula@ee.umanitoba.ca (N.W.A. Lidula), athula@ee.umanitoba.ca (A.D. Rajapakse).
[1] Tel.: +1 480 1403; fax: +1 204 474 7522.

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1. Introduction

Microgrids are emerging as an integral feature of the future power systems shaped by the various smart-grid initiatives. A microgrid is formed by integrating loads, distributed generators (DG) and energy storage devices. Microgrids can operate in parallel with the grid, as an autonomous power island or in transition between grid-connected mode and islanded mode of operation.

A microgrid could be an attractive option to harness the benefits offered by distributed generation, eliminating the constraints on high penetration. Thus, substantial environmental benefits may be gained through the utilization of energy efficient generation resources and the integration of renewable energy resources. Moreover, microgrids could reduce the network losses, defer the high investment costs required for network upgrades and also reduce the central generation reserve requirements. DGs provide local voltage support and microgrid as a whole increases the overall system reliability [1–6].

This paper reviews the current status of the development of microgrids. This will cover a brief description on components of a microgrid and a literature review on existing microgrid test systems that have been implemented and simulated. The paper contributes as a particularly focused resource, which consolidates existing microgrid research experiences in an organized structure. It guides the reader to visualize the present big picture of the microgrid and allows understanding the potential developments. Furthermore, the comparison of microgrids in several continents provides useful information for the design and choosing the right features for a particular microgrid application. It is also envisaged that the information summarized in the paper contributes to open research beyond the existing trends.

2. The picture of a microgrid

A microgrid is encompassed of variety of distributed generators (DG), distributed storages (DS) and variety of customer loads. It is particularly a portion of an electric power distribution system located downstream of the distribution substation. Thus, the microgrid point-of-common-coupling (PCC) lies at the vicinity of the low voltage side of the substation transformer.

2.1. Distributed generators

Generation technologies applicable for a microgrid may include emerging technologies (Combined heat and power (CHP), fuel cells, mini wind turbines, PV, micro-turbines) and some well established generation technologies (single-phase and three-phase induction generators, synchronous generators driven by IC engines or small hydro). These generation technologies are well known [1,2] and thus, it is not discussed in detail in this paper. Nevertheless, it is important to note that CHP (also known as cogeneration, which produce electricity and heat simultaneously) and wind power generation has shown considerable growth in technology and usage gaining strong points to be used in microgrids.

Almost all large integrated power systems in the world have been relying on centralized electricity generation such as large-scale hydro, coal, natural gas and nuclear power plants. Long-distance, high-voltage transmission carried the power to the customers from centralized sources. However, the growth of demand for clean, reliable and affordable electricity generation is changing this existing scenario. On the other hand, the aging centralized energy infrastructure, which can be more vulnerable with the increasing power demand, requires innovative and economical solutions as the construction of new transmission facilities is highly constrained by the environmental considerations. Many governments in the world have responded to these demands with suitable policy adjustments that encourage distributed and renewable energy generation. As a result, the share of renewable and efficient DGs is rapidly increasing. For example [7] reports that in Canada, as of 2005, 25% of new electricity generation installed has come from distributed resources, compared to only 13% in 2002.

2.2. Energy storage devices

Energy storage devices are one of the main critical components to rely on for successful operation of a microgrid. The main function of the energy storage devices in a microgrid application is to be the care taker in balancing the power and energy demand with generation. Energy storage devices take this responsibility in three necessary scenarios.

1. Insure the power balance in a microgrid despite load fluctuations and transients as DGs with their lower inertia lack the capability in fast responding to these disturbances.
2. Provides ride-through capability when there are dynamic variations in intermittent energy sources and allows the DGs to operate as dispatchable units.
3. Provides the initial energy requirement for a seamless transition between grid-connected to/from islanded operation of microgrids.

Among the available energy storage technologies [8,9], batteries, fly-wheels and super-capacitors are more applicable for microgrid type of setup [10]. In the use of a flywheel, it can be used as a central storage system for the whole microgrid. In the use of batteries, either storage can be mounted on the dc bus of each micro-source or can be used as a central storage system. Batteries provide extra function being able to reserve energy for future demand. Super capacitors would be an expensive choice compared to both batteries and flywheels [8]. Another option is to have a large traditional generation having considerable inertia along with the micro-sources.

2.3. Interfacing distributed energy resources (DER)

Distributed energy resources (DER) refer to both DG and energy storage technologies. Most of the emerging DER technologies require an inverter interface in order to convert the energy into grid-compatible ac power. This interfacing may either consist of

both converter and inverter or only an inverter. The power electronic interface will be accommodated with filters and necessary protection systems. With the converter's capability of voltage and frequency control, these DER units support the microgrid operation. Table 1 summarizes the interfacing and power flow control options of common DER.

2.4. Microgrid loads

A microgrid could serve variety of customers: residential, commercial and industrial. In general, commercial and industrial users are defined as critical/sensitive loads, which demand high degree of power quality and reliability. This classification of loads is important in the microgrid setup to achieve the expected operating strategy:

1. Facilitate load/generation shedding within the microgrid to meet the net import/export power in grid connected mode.
2. Facilitate load/generation shedding to stabilize the voltage and frequency in the autonomous operation.
3. Improve the power quality and reliability of critical and sensitive loads.
4. Reduces the peak load to optimize the ratings of DER.

Part of the non-sensitive loads can be used as controllable loads to achieve the above operating strategies in a microgrid [11,13].

2.5. Interconnection of microgrids

Microgrids get connected to the power system at the distribution level. Also, energy handling capability of microgrids is limited with the use of renewable energy resources and waste heat. Thus, maximum capacity of a microgrid is normally restricted to 10MVA [2].

Microgrid is connected to the utility system via an interconnection switch. If the microgrid consists of voltage-sensitive loads such as semiconductor manufacturing, it requires separation times of less than 50 ms [2]. However, the existing protective equipment and circuit breakers are not capable to act that fast to isolate and change the mode of control in the microgrid. In such a condition it is required to maintain the voltage above 50% of the rating at any time of operation [2].

Consequently, the recent research has applied static switches with fast response or Digital Signal Processor (DSP) based switches that consolidate both power switching and relaying, as the interconnection method [14,15].

2.6. Control and communication strategies used

The main advantage expected from a microgrid is that it should allow to be treated as a controlled aggregated load within the power system. Also, being in the vicinity of smart grid systems, microgrids should facilitate adaptive control approaches.

The present research in microgrids adopts control approaches that could be imbedded as autonomous parts of each distributed generator, use a central controller or based on agents. Autonomous control allows placing additional DGs without reengineering the system, and using it in the peer-to-peer model (using ($N + 1$) DERs in the system) eliminates the requirement of a complex central controller and associated telecommunication facilities. The agent based system facilitates both centralized co-ordination and local control as it operates in different levels as a hierarchy. This approach allows utilization of the strengths of both central and decentralized control systems and this is a possible candidate for future smart grid approaches.

Communication can be one of the most vital elements in a microgrid, particularly for power control and protection. The basic communication methods used so far include: radio communication, leased telephone lines, power-line carrier, internet and Global System for Mobile (GSM) Communications. The present microgrid experiments have used different communication protocols, but establishment of some standard communication protocol could help reduce costs and accelerate the deployment of microgrids.

3. Experimental microgrids and microgrid test-beds

Microgrid is a subject that has been studying and testing around the world in the recent past. The thriving interest on microgrids is reflected by the forthcoming IEEE Std P1547.4 on *Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems* [16] which is specifically developed to address the missing information in IEEE Std 1547-2008 [17] regarding intentional islands.

There is no particularly accepted benchmark test system for microgrids. The research works on microgrids are based on either test-beds or simulations using different microgrid topologies. There are some typical microgrid configurations also reported. In this section, it is attempted to summarize the microgrid test systems reported in the literature.

3.1. Intentional islanding and microgrid experience around the world

3.1.1. Boston Bar – BC Hydro, Canada

The BC Hydro Boston Bar is a microgrid that is interconnected to 69 kV feeder through a 69/25 kV substation comprising of three radial feeders. It was built as a solution to the frequent experiencing power outages between 12 and 20 h periods that happens due to permanent outages on the 69 kV line connecting the substation to the BC Hydro grid.

Fig. 1 presents the single-line diagram of the Boston Bar system [10,18]. The microgrid comprises of two 4.32 MVA run-of-river hydro power generators connected to one feeder. The peak load of

Table 1
Typical interfaces used with DER [11,12].

Primary energy source type		Typical interface	Power flow control
DG	CHP	Synchronous generator	AVR and Governor (+P, ±Q)
	Internal combustion engine	Synchronous or induction generator	
	Small hydro	Synchronous or induction generator	
	Fixed speed wind turbine	Induction generator	Stall or pitch control of turbine (+P, −Q)
	Variable speed wind turbine	Power electronic converter (AC–DC–AC)	Turbine speed and DC link voltage controls (+P, ±Q)
	Micro-turbine	Power electronic converter (AC–DC–AC)	
	Photovoltaic (PV)	Power electronic converter (DC–DC–AC)	Maximum power point tracking and DC link voltage controls (+P, ±Q)
	Fuel cell	Power electronic converter (DC–DC–AC)	
Energy storage	Battery	Power electronic converter (DC–DC–AC)	State of charge and output voltage/frequency control (±P, ±Q)
	Fly-wheel	Power electronic converter (AC–DC–AC)	Speed control (±P, ±Q)
	Super capacitor	Power electronic converter (DC–DC–AC)	State of charge (±P, ±Q)

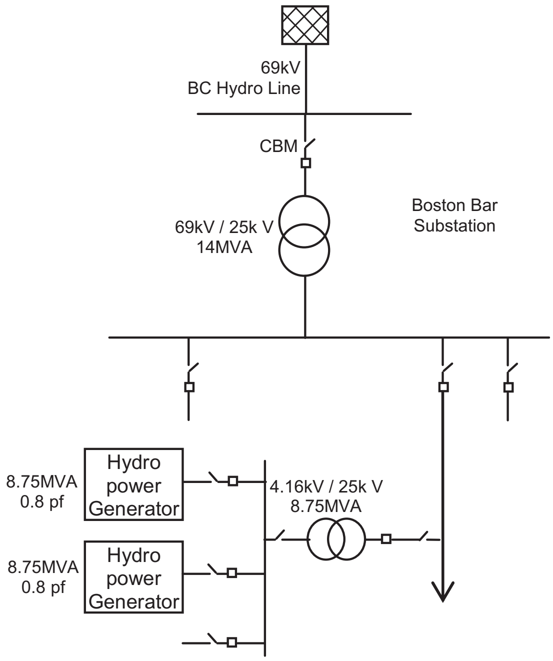

Fig. 1. Single-line diagram of the BC Hydro Boston Bar system.

the microgrid is 3 MW and depending on the demand and water level, it supplies power to one or more feeders by sectionalizing loads accordingly.

The system is not equipped with a storage unit, but the inertia of the generators has increased purposely. A leased telephone line is used for communication. The controlling options include:

1. Generators operate in isochronous mode in single generator operation and governor speed-droop control is used in parallel operation.
2. Transient response is improved by engineering mass of generators and hydro turbines, thus increasing inertia.
3. Automatic voltage regulation (AVR) control is used to regulate voltages at the Point of Common Coupling (PCC).
4. Two sets of over current protection set-points for the grid-connected and the islanding operating modes.
5. To supply high fault current during a feeder fault, the excitation system control is made with positive voltage field forcing for output current boost.
6. When the island happens substation breaker open position is telemetered via leased telephone line between the generator(s) remote control site and the utility Area Control Centre.
7. Black start capability is provided via an on-site 55 kW diesel generator if the generator(s) fail to sustain the island.
8. Remote auto-synchronization capability is added at the substation level to synchronize and re-connect the island area to the 69 kV feeder without causing load interruption.

3.1.2. Boralex planned islanding – Hydro Quebec (HQ), Canada

The substation named Senneterre in Quebec feeds three distribution lines, serving 3000 customers. The substation is supplied at 120 kV by a 40 km long transmission line which had required an urgent replacement. The Boralex thermal power plant is connected through the Senneterre substation to the HQ Network. Thus, the restoration of the transmission line has done by using the Boralex power plant for islanding of HQ's Senneterre substation. The generator has shown stable operation in isochronous mode under varying loads. The peak load tested was around 7 MW. Fig. 2 presents the planned islanding with Boralex plant at the Senneterre Substation [18].

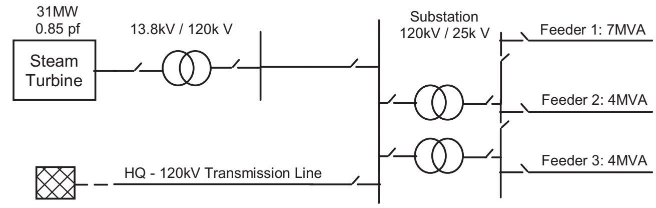

Fig. 2. Planned islanding with Boralex plant at Senneterre Substation.

Since this system is operated with a single, comparatively large generator and operated as an island only during the planned system maintenance, it does not use any storage or communication system.

3.1.3. The CERTS testbed – United States

The CERTS testbed is a full-scale testbed built near Columbus, Ohio and operated by American Electric Power. The testbed has three feeders. One feeder has two 60 kW converter based sources driven by natural gas. Other feeder has a single source of same type and capacity. Third feeder is connected to the utility but, it could be powered by the DGs when static switch is closed without injecting power to the utility. Each generator set is provided with battery energy storage at its DC bus. Fig. 3 presents the one-line diagram of the CERTS microgrid testbed [10,19].

A central communication system based on Ethernet is used to connect the Energy Management System (EMS) and the generator sets to dispatch DG set points. However, this communication network is not used in dynamic control of the microgrid. Thus, the power sources are in autonomous control with plug-and-play capability.

There is no central controller in the CERTS microgrid allowing the power sources to be operated in peer-to-peer fashion (considers $(N+1)$ sources in operation, thus loss of a component does not disturb the microgrid functioning).

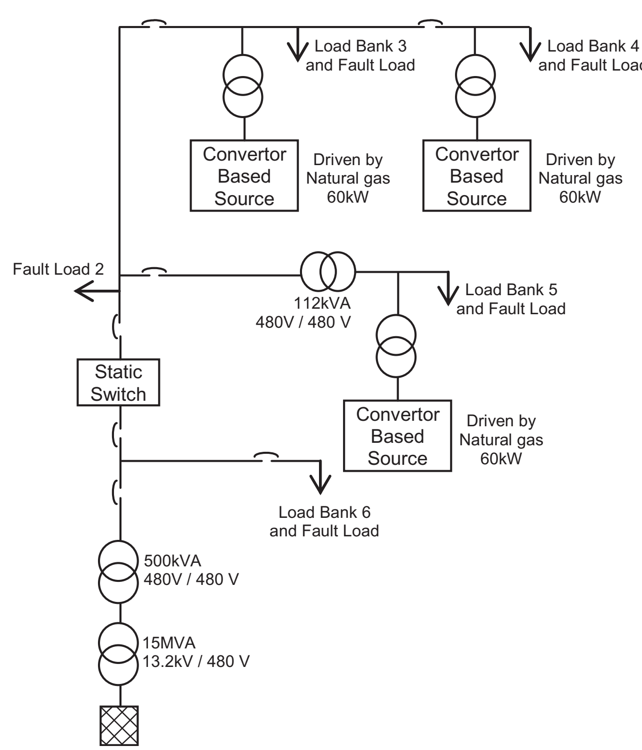

Fig. 3. CERTS microgrid testbed.

The controlling options of the CERTS microgrid include:

1. Each source control the power using the real power versus frequency droop and thus, sources are coordinated through frequency.
2. The voltage is maintained using the reactive power versus voltage droop and thus, providing local stability and it insures there are no circulating reactive currents between sources.
3. The thyristor based static switch is capable of autonomously island the microgrid at disturbance such as faults, IEEE 1547 events or power quality events.
4. Resynchronization is achieved by using the frequency difference between the islanded microgrid and the utility grid.

3.1.4. UW microgrid – United States

UW microgrid testbed at the University of Wisconsin – Madison shown in Fig. 4 is implemented to investigate the modeling and control issues in integrating diesel generators into microgrids that can also include convertor based sources [20].

The possibility of having energy storage with the converter based system is discussed, but the availability is not clearly mentioned in [20]. It also discusses that having a position sensor such as an encoder or resolver mounted on the shaft of the generator set avoids the requirement of any communication system, but does not present any further discussion of such methodology.

The diesel generator in the microgrid is equipped with a conventional mechanical governor to control the frequency at a droop of 3 Hz and a voltage controller that regulates the terminal voltage to a fixed value. However, the convertor based source is operated with real power versus frequency droop of 0.5 Hz. The experiments have revealed the microgrid is stable in islanded mode but, has presented large circulating VAR flows in the system.

The following controlling modifications are further proposed with simulation results to insure the system stability:

1. To replace the mechanical governor with an electronic actuator that utilizes a PWM command to vary the fuel input to the engine.
2. To use a reactive power versus voltage droop, where the output of the brushless exciter is controlled accordingly by varying the input current of the exciter machine.

3.1.5. Bronsbergen Holiday Park microgrid – Netherland

This is one of the *More Microgrids projects* that were supported by the European Union. Bronsbergen Holiday Park consists of 208 holiday homes. The microgrid is formed in the park and the generation comes from 108 roof fitted solar PVs and the peak generation capacity is 315 kW. The microgrid is connected to a 10 kV medium voltage grid through a 400 kVA transformer (400 V/10 kV) [10,21]. The system is equipped with a central energy storage, which comes by two battery banks connected at the point of common coupling. Fig. 5 presents the schematic diagram of the Bronsbergen Holiday Park microgrid.

The controlling options of the Bronsbergen Holiday Park microgrid include:

1. Central control method is used.
2. Active and reactive power of each feeder is measured and sent to the central controller, which measures the total amount of active and reactive power exchanged between the micro grid and the mid-voltage grid.
3. The central controller exchanges the data with the computer at the dispatch center, via GSM communication.
4. Automatic isolation and reconnection is available (method is not explained in the literature).

3.1.6. The Residential Microgrid of Am Steinweg in Stutensee – German

This test system is built to test the work carried under the *DISPOWER* project. Am Steinweg microgrid is a three-phase low voltage (400 V) four-wire system, which is connected to the medium voltage (20 kV) network through a 400 kVA transformer. The energy sources in this system consist of a CHP with available electrical power of 28 kW, different PV installations with nominal power of 35 kWp and a lead acid battery bank with a rating of 880 Ah. The battery is connected via a bi-directional inverter of 100 kW. The batteries can deliver this power for half an hour. In total, 101 apartments are linked to the microgrid. The maximum active power through the transformer is determined as 150 kW [22,23]. A schematic diagram of the microgrid is shown in Fig. 6.

The test system is operated using a *Power Flow and Power Quality Management System (PoMS)*. PoMS is a low voltage grid optimization tool that manages grid operation, DG control and demand side management. PoMS consists of a central unit (PCU) and several decentralized PoMS interface boxes (PIBs). Controllable grid devices and measuring devices communicate with PCU through the PIBs. The communication medium used in this test system is Transmission Control Protocol and Internet Protocol (TCP/IP), which is the standard for communication in computer networks. It is reported that the system has the possibility of islanded operation and is capable of matching energy demand for longer periods [22].

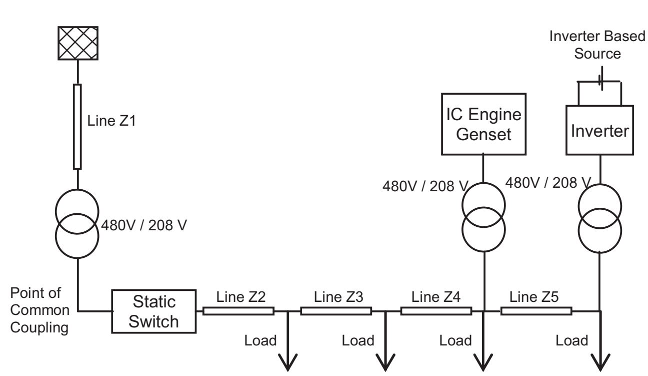

Fig. 4. UW microgrid testbed.

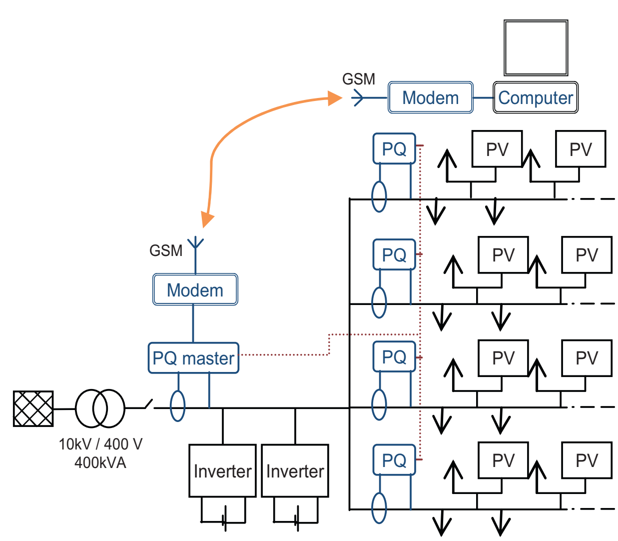

Fig. 5. Schematic diagram of the Bronsbergen Holiday Park microgrid.

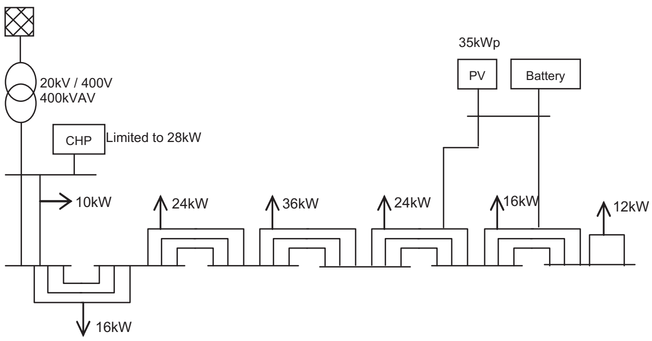

Fig. 6. Schematic diagram of the residential microgrid of Am Steinweg in Stutensee.

3.1.7. CESI RICERCA DER test microgrid – Italy

This is a low voltage (400 V) DC microgrid that is connected to the medium voltage (23 kV) grid by means of 800 kVA transformer. It is constituted by several DERs and controllable loads [22]. Fig. 7 presents the network configuration of CESI RICERCA DER test microgrid. This test system is also comes under *More Microgrid* projects.

Centralized control is used in this system. DERs and the controllable loads of the system are connected to the Supervision & Control System (SCS), named URA and a hierarchical scheme is used to communicate and process information. The SCS has been set up in order to record and analyze the experimental data derived from the field tests, to monitor power quality and electrical transients and to communicate the on-line information to the dispatcher and control system. Optimization techniques are used to schedule the set-points. The communication system is based on wide band power-line carrier technology, and wireless technology that requires a 2.4 GHz radio channel.

The system is equipped with a fly wheel for power quality purposes and several battery banks as energy storages. Local droop control systems implemented in the two zebra batteries and Lead acid battery, ensure proper system operation during fast transient dynamics and in islanded mode [22,24].

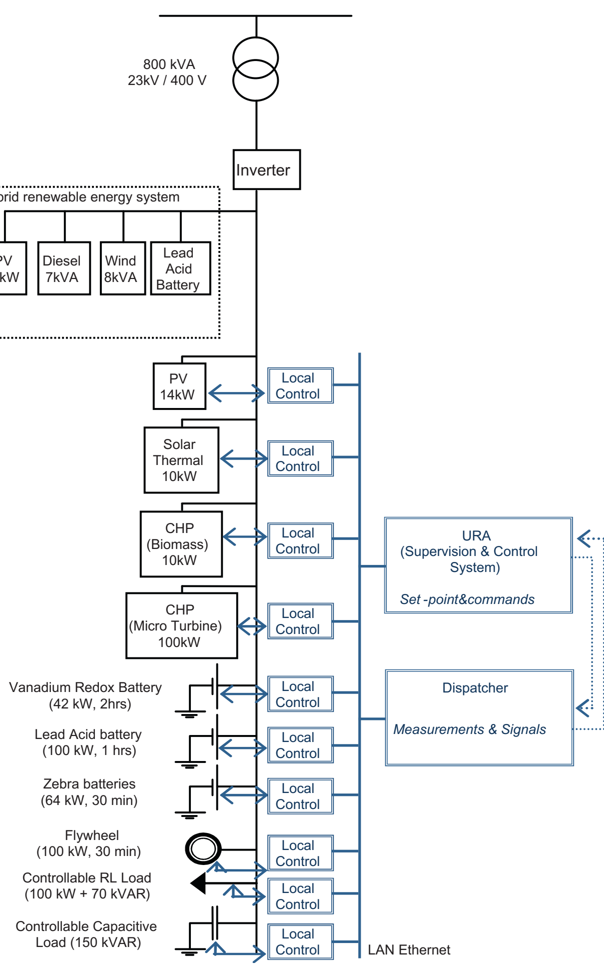

Fig. 7. CESI RICERCA DER test microgrid network configuration.

3.1.8. Kythnos island microgrid – Greece

The Kythnos island microgrid shown in Fig. 8, electrifies 12 houses having load controllers and the generation constitute of 10 kW of PV, a nominal 53 kWh battery bank, and a 5-kW diesel generator set. A second PV array of about 2 kW, mounted on the roof of the control system building, is connected to an SMA inverter and a 32 kWh battery bank to provide power for monitoring and communication. Residential service is powered by three SMA battery inverters connected in a parallel and these battery inverters can operate in frequency droop mode.

Grid frequency is used as communication signal for advanced battery management in addition to the frequency droop concept. The battery inverters are tuned to vary the grid frequency for providing control information to the distributed PV string inverters and the load controllers. When the state of charge of the battery is low, the controllable loads are tripped off thus reducing the consumption, and when the battery bank is approaching full charge, PV inverters are able to sense this and they continuously de-rate the power outputs [25].

3.1.9. Laboratory-scale microgrid system at National Technical University of Athens (NTUA) – Greece

NTUA microgrid test system shown in Fig. 9 comprises of two PV generators, one wind turbine, battery energy storage, controllable loads and a controlled interconnection to the local LV grid.

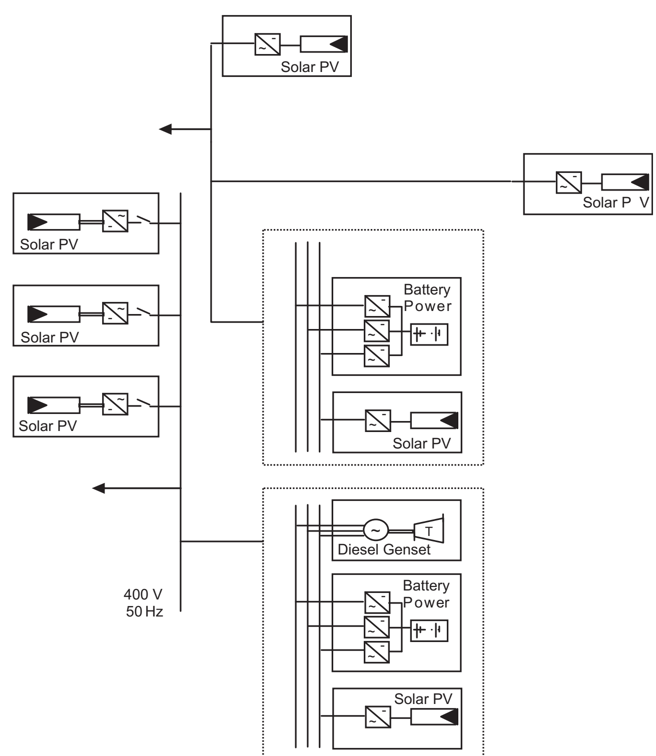

Fig. 8. The Kythnos island microgrid.

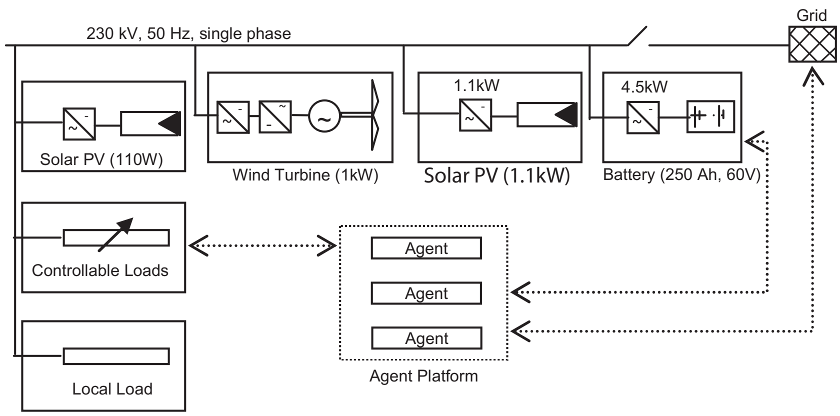

Fig. 9. The laboratory microgrid facility at NTUA.

Generators are connected to the AC grid via fast-acting inverters. The battery is connected via a bi-directional PWM voltage source converter, which regulates the voltage and frequency when the system operates in the island mode. The battery inverter operates in voltage control mode (regulating the magnitude and phase/frequency of its output voltage). When the microgrid operates in parallel to the grid, the inverter follows the grid. The system is built on the Java Agent Development Framework (Jade) 3.0 platform, thus communication language could be either XML or SL [26].

Operation planning of this test microgrid is done using a Multi Agent System (MAS), which consists of four agents:

- Production Unit:

  Responsible to control the inverter of the battery. The main tasks are to control the overall status of the batteries and to adjust the power flow depending on the market prices.
- Consumption Unit:

  Represents the controllable loads in the system. It knows the current demand and makes estimations of the energy demand for the next 15 min. At every 15 min it makes bids to the available *Production Units* in order to cover the estimated demand.
- Power System:

  Represents the main grid to which the microgrid is connected. According to the market model adopted, the *Power System Agent* announces the selling and buying prices. It does not participate in the market operation since it is obliged to buy or sell any amount of energy asked for.
- Microgrid Central Control (MGCC):

  MGCC is responsible to announce the beginning and the end of a negotiation for a specific period and to record the final power exchanges between the agents in every period.

3.1.10. DeMoTec test microgrid system – German

DeMoTec test microgrid consists of two battery units, two diesel gensets, PV generator and a wind generator. The total available generation capacity is approximately 200 kW. There are several loads with different priority levels and several automatic switches are there for sectionalizing the microgrid into up to 3 low voltage island grids. All generators and loads can be connected via a central crossbar switch cabinet to a local grid. The system is equipped with some centrally connected battery banks (one of them is a simulated battery bank) and some single phase battery inverters connected with single phase PV systems. Fig. 10 presents the one-line diagram of the DeMoTec test microgrid.

A Supervisory Control and Data Acquisition System (SCADA) is used to control the generators and to enable a monitoring of the operating states of the system. The communication is done via a separate Ethernet communication line, and XML-RPC communication protocol is used [22,26].

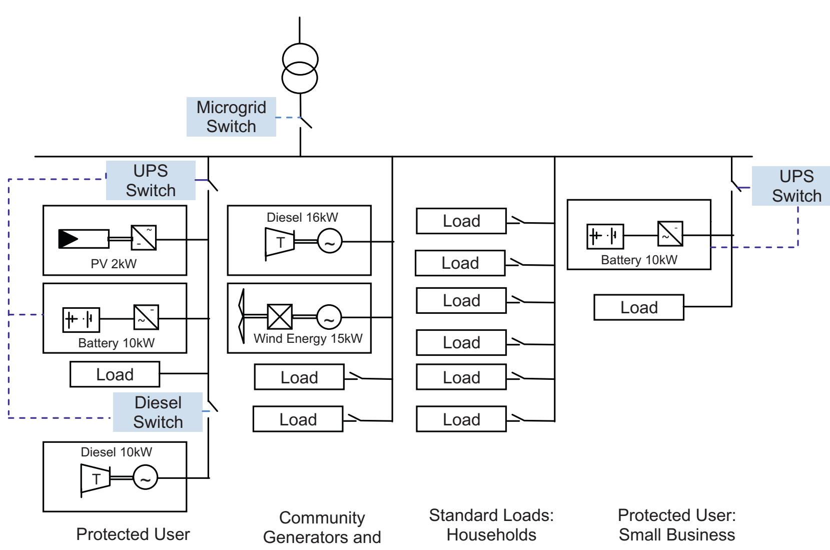

Fig. 10. DeMoTec microgrid test system.

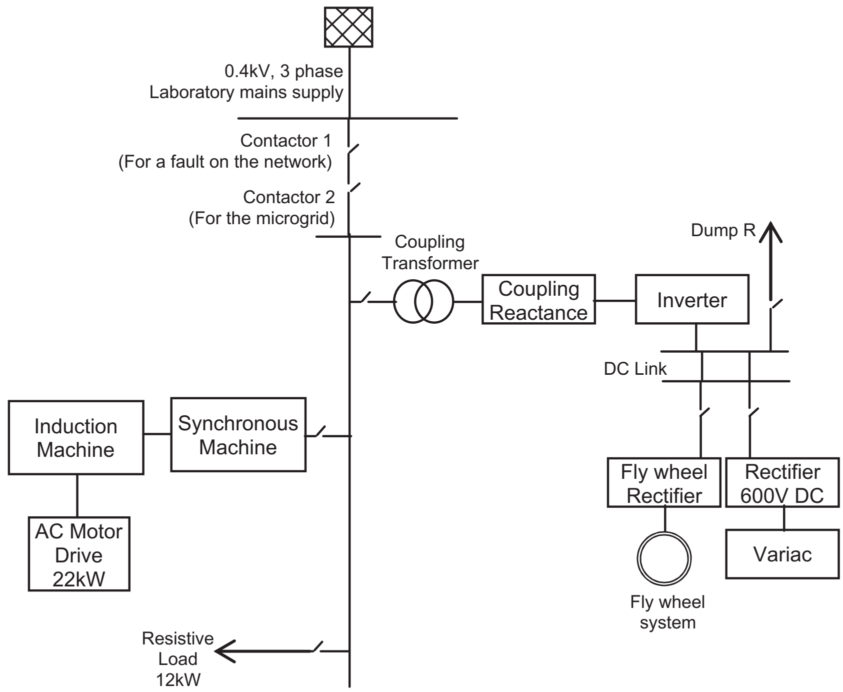

Fig. 11. University of Manchester microgrid/flywheel energy storage laboratory prototype.

3.1.11. University of Manchester microgrid/flywheel energy storage laboratory prototype – UK

Fig. 11 shows the block diagram of the microgrid test system built at the University of Manchester. The system is nominally rated at 20 kVA. A synchronous generator and an induction motor coupled together acts as the micro-source while a flywheel connected through an inverter is serving as the energy storage system. The flywheel is 100 kW unit down rated to 20 kW power output. A three-phase balanced load of 12 kW is connected at the end of the feeder. The 0.4 kV mains supply of the laboratory is considered as the main grid.

The flywheel system is connected to the microgrid through two *Intelligent Power Module* (IPM) units, coupling reactance and a coupling transformer. The flywheel inverter system sets the voltage and frequency reference in the islanded mode, maintain the voltage and frequency of the microgrid (using active power versus frequency droop and reactive power versus reactive power droop) and also supply enough fault current to operate protection

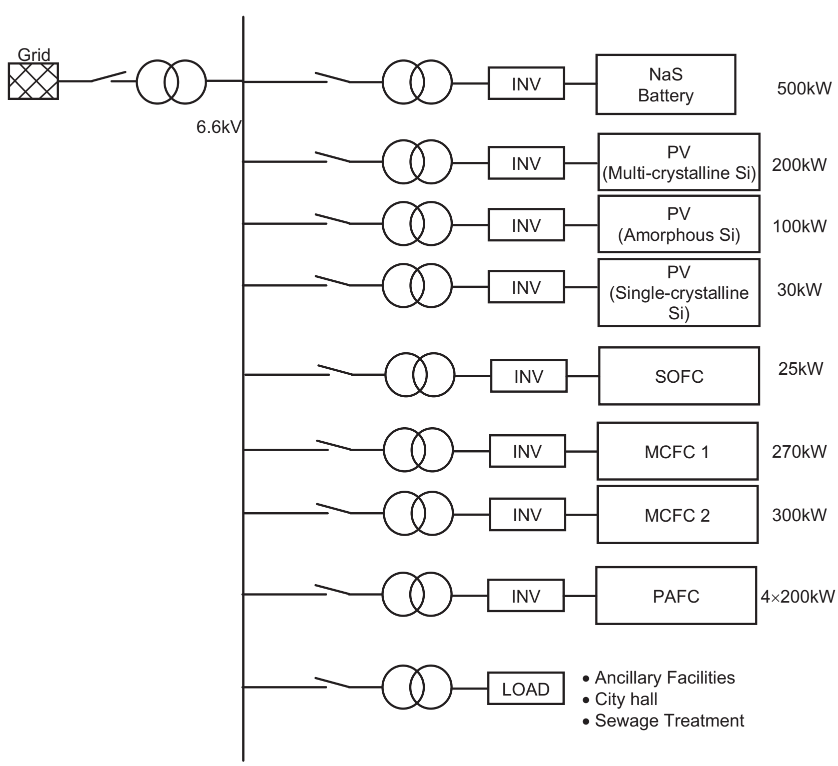

Fig. 12. Aichi microgrid project single-line diagram.

devices during a disturbance. The inverter coupling reactors are designed to work in conjunction with the IPM inverters and the three 8 kVA single-phase coupling transformers. The primary function of the transformers is to provide isolation between the power electronics and the microgrid.

When the flywheel is not being run, a 600 V DC rectifier is connected through a variac to the laboratory mains to supply a DC link voltage to the IPM units. This unit also provides the flywheel with a variable DC voltage for various start-up procedures. Once the flywheel is fully up to speed, this unit can be disconnected, with the IPM units taking over power flow to and from the flywheel. A dump resistance with a load magnitude of 12 kW is connected for dissipating excess energy and for quick discharging of the DC link. The communication requirement is not discussed for this test system [26,27].

3.1.12. Aichi microgrid project – Central Japan airport city

Aichi microgrid is built as part of a demonstrative project commissioned by the New Energy and Industrial Technology Development Organization (NEDO). NEDO projects operates with a control target that is set to maintain a margin of error between supplied energy and consumed energy over a certain period.

The Aichi microgrid consists of a power supply system having fuel-cells (two molten carbonate fuel-cells (MCFCs) with capacities of 270 kW and 300 kW, one 25 kW solid oxide fuel-cell (SOFC), and four 200 kW phosphoric acid fuel cells (PAFCs)), PV of 330 kW, and a sodium-sulfur (NaS) battery storage system, all equipped with converters. The fuel of MCFC is a mixture of biogas, high-temperature gasified gas, and town gas (extracted from natural gas). Biogas is produced by methane fermentation system treating garbage onsite. High-temperature gasified gas is produced by a high-temperature gasification facility treating PET bottles and waste wood on site. Single-line diagram of the Aichi microgrid is shown in Fig. 12 [28,29].

The battery converter takes the responsibility to match the supply and demand and to control the voltage. Also a day-ahead generation planning is done using an optimization technique that applies genetic algorithm and a tabu search called a meta-heuristic technique. A telecommunication network is used as the medium of communication.

3.1.13. Kyoto eco-energy project (Kyotango project) – Japan

Kyoto Eco-Energy project is also carried out under NEDO projects. This is considered as a *virtual microgrid* because as shown in Fig. 13, each DER and demand site is connected to a substation of the utility grid and they are only integrated by a control system.

The microgrid is formed by a plant having gas engines with a total capacity of 400 kW, a 250 kW MCFC and a 100 kW lead-acid battery, and two PV systems and 50-kW small wind turbine connected at remote locations.

Remote monitoring and controlling is used to meet the energy demand through available power generation. The decisions are made in a central controller and the communication is made through standard ISDN or ADSL ISP connections to the Internet, which are the only connection options available in that rural area of Japan [30].

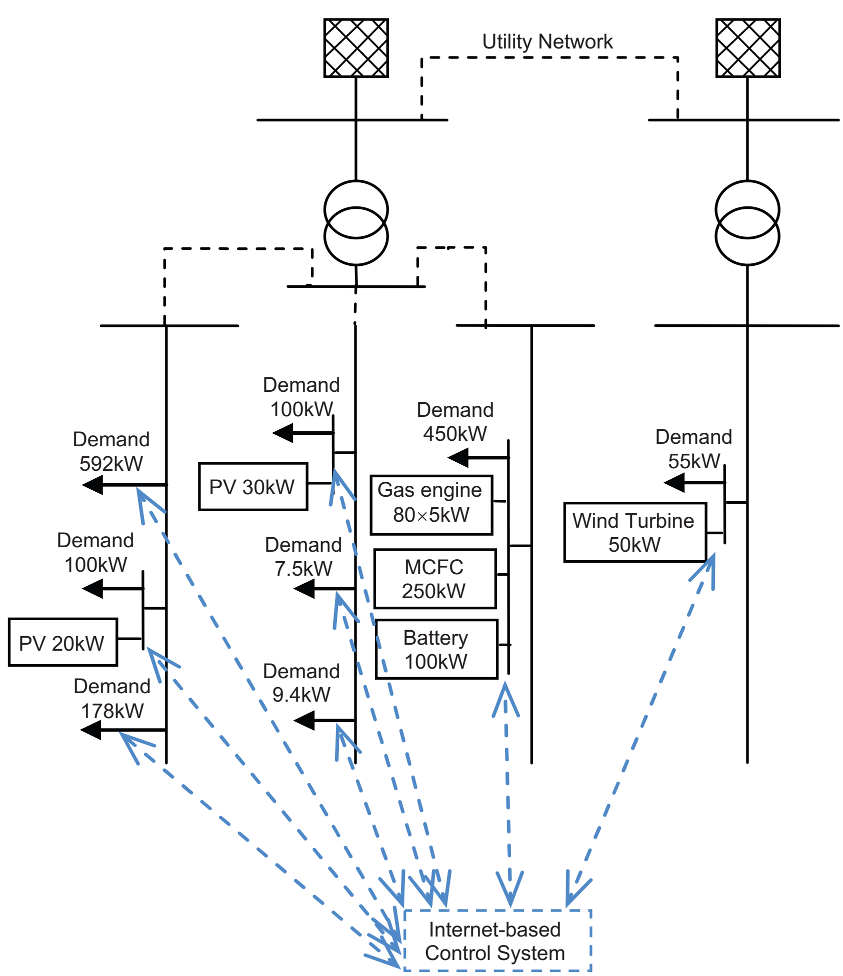

Fig. 13. Kyoto Eco-Energy virtual microgrid schematic diagram.

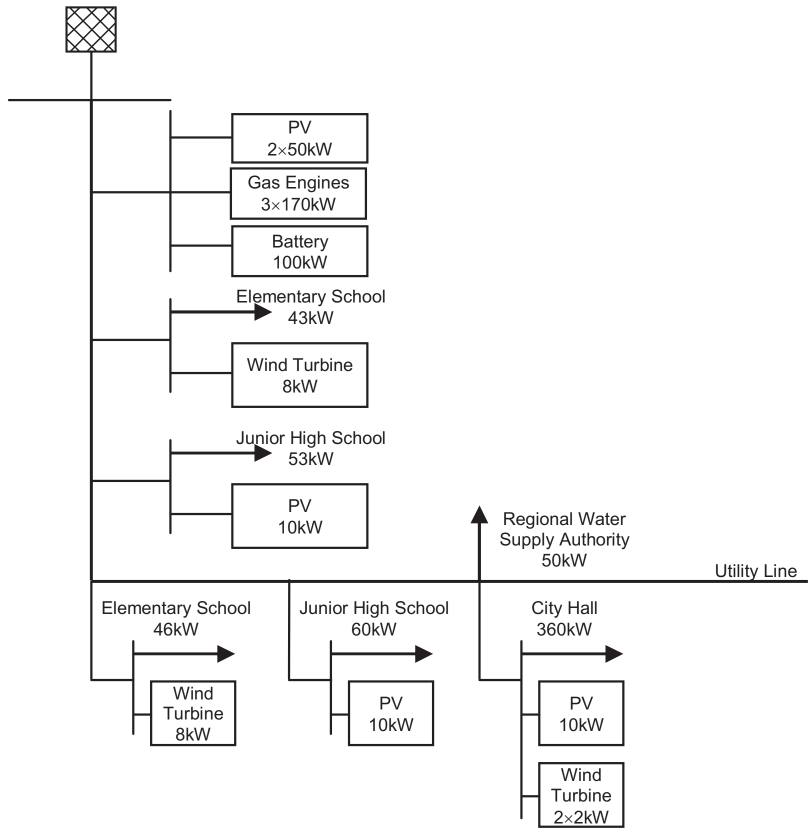

Fig. 14. The schematic diagram of the Hachinohe microgrid.

3.1.14. Hachinohe project – Japan

The Hachinohe is a microgrid that is carried under NEDO projects and it is built based on a private distribution line, which is used for both electricity distribution and communication. The system consists of a gas engine system (3×170 kW), several PV systems (2×50 kW one plant and 3×10 kW dispersed) and a small wind farm (2×2 kW one plant and 2×8 kW dispersed). To safeguard the microorganisms that produced digestion gas in the sewage treatment plant, a wood waste steam boiler was also installed because thermal heat was in short supply. Four schools and a water supply authority office are connected to the private distribution line. The system is equipped with a 100 kW battery storage. Fig. 14 presents the schematic diagram of the Hachinohe microgrid.

The control system used to balance supply and demand consists of three facets: weekly supply and demand planning, economic dispatch control once every 3 min, and second-by-second power flow control at interconnection points. To overcome the issue of power imbalance among the three phases a new PV inverter that could compensate for the imbalances among the three phases is installed and operated [10,30].

3.1.15. Test network at Akagi of the Central Research Institute of Electric Power Industry (CRIEPI) – Japan

This project is aimed to evaluate new test equipment under integrated control. Block diagram of the test system is shown in Fig. 15. The test system emulates PV generation derived through 3×100 kW inverters from the power supply room and 200 kVA dummy loads consist of resistances and reactances. Equipments in the test system included a static var compensator (SVC), a step voltage regulator (SVR) and loop balance controllers (LBCs) for the purpose of power control. Energy storage is not included in this system.

Test system is operated with a central controller connected to the other equipment with fiber optics communication. The SVC and SVR are used to regulate the voltage in the 6.6 kV distribution feeder, and sometimes used with an actual utility network. LBCs are a new type of distribution network equipment that can control the power flow between two distribution feeders by means of a back-to-back inverter. In this project, two types of LBCs are developed. The first is a 500 kVA mini-prototype with a transformer and the second of 1000 kVA is a new concept model without a transformer. Having the DC link LBCs allow connection of DERs at different voltages and frequencies [30,31].

3.1.16. Sendai project – Japan

Sendai microgrid test system shown in Fig. 16, consist of two 350 kW gas engine generators, one 250 kW MCFC, 50 kW PV, battery energy storage and various types of compensating devices. There is also a remote measurement and control system, which is responsible for monitoring the facilities, GPS synchronized measurement data acquisition, and gas engine output controlling. MCFC is always operated at a preset constant output.

The compensating equipment include an integrated power quality backup system that supply high quality power to "A" class consumers and "B1" class consumers, those who used on-site UPS backup systems previously. The wave pattern is guaranteed only for "A" consumers. In the case of "B2" and "B3" class consumers, only short-term voltage drops were compensated for by a series compensator. The integrated power quality backup system, which also includes the battery energy storage and a static switch, can operate in several modes of operation. The applicable mode of operation at a given time is determined by the central controller [30,32].

3.1.17. Microgrid testbed in Hefei University of Technology (HFUT) – China

The testbed consists of PV generators (10 kW single-phase and 30 kVA three-phase), three-phase wind generation simulators

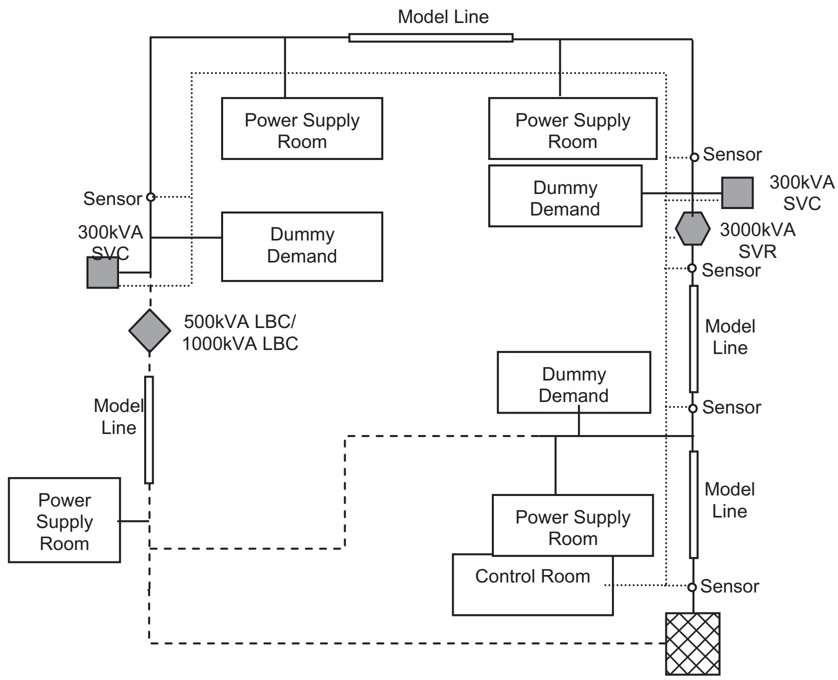

Fig. 15. Structure of test network at CRIEPI.

(2 × 30 kW), fuel cell (5 kW), battery bank (300Ah), ultra-capacitor bank (1800F × 110), conventional generators (2 × 15 kW) used to simulate the small hydro and small fossil generators and various loads (resistors, capacitor, inductors, AC and DC motors and other electronic loads). The AC buses include two voltage levels (400 V, 800 V). Fig. 17 presents the schematic diagram of the testbed.

Controlling is done under two-layers: local controllers and central controller as shown in Fig. 18. The local controllers are integrated in the inverters for each DG and they are responsible for controlling feed bus power flow, voltage and frequency, automatic control of seamless operation mode change, power quality control and protection.

The central controller is used to start up and shut down the operation of the microgrid and to produce the optimal schedule for each DG and real time control decisions (15 min, 30 min or an hour ahead) according to predicted results about fluctuant energy resources, such as solar energy and wind energy, and the economic dispatching strategies for balancing microgrid power. The test system is managed with an energy management system (EMS) that conforms to the IEC 61970 CIM standards and it comprises of a supervisor control and data acquisition (SCADA) system, automatic generation control (AGC) and power system application software (PAS) [33].

3.1.18. Laboratory scale microgrid – China

The microgrid is built attached to a single phase system of 230 V, 50 Hz and it comprises of PV simulator, wind simulator and battery storage. Interconnection of the micro-sources to the grid is

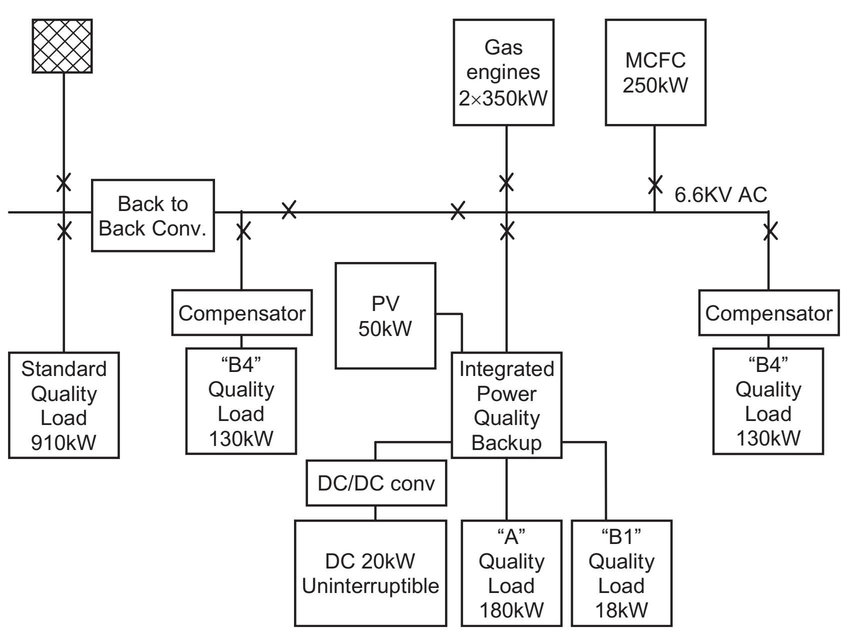

Fig. 16. The schematic diagram of the Sendai microgrid.

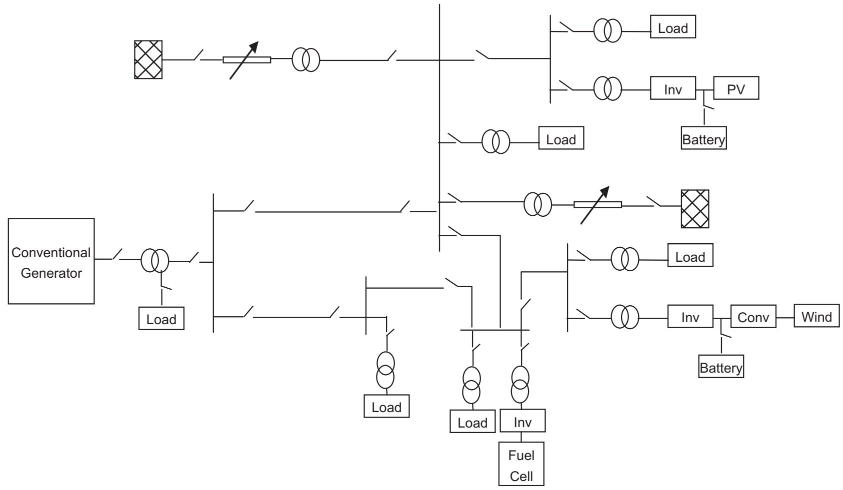

Fig. 17. Microgrid testbed in Hefei University of Technology.

made via flexible power electronic interfaces. Fig. 19 presents the schematic diagram of the microgrid.

Central controlling option is used to balance the power in the microgrid. Communication is made through RS485 lines. The controlling phases are changed over the mode of operation: In grid connected operation micro-sources operate as fixed PQ generators and battery inverter allows grid following. In island mode the battery inverter is operated in voltage control mode. DGs are operated as fixed PQ generators and this mode of operation is changed at times when battery is fully charged. To prevent the excess energy from overcharging the batteries, the battery inverter is set to recognize when battery is fully charged and to change the frequency of the AC output. As soon as the grid frequency increases beyond a threshold, the micro-sources are set to limit their output power according to a set active power versus frequency droop. In switching the mode of operation, the switching is done via a static switch and the battery inverter operates in voltage control mode maintaining the voltage and frequency in the island [34].

3.1.19. Test microgrid at the Institution of Engineering and Technology – India

This laboratory scale microgrid model consists of two PSO-based inverters fed from fuel cell stacks, sine PWM inverter connected to an uncontrolled rectifier fed from a DC motor-driven induction generator (2.2 kW, 415 V, 50 Hz, three-phase, 0.85 p.f. and the rotor is of squirrel cage type).

The grid capacity considered for the experimental set-up is 3.2 kVA, 415 V, three-phase and 50 Hz. Fig. 20 presents the schematic diagram of the test setup. Voltage and frequency control is done via the PWM inverter. The requirement of energy storage or communication system is not discussed [35].

3.2. Test systems for microgrid simulation studies

3.2.1. A benchmark low voltage microgrid network

This microgrid simulation model is developed based on the CIGRE low voltage (LV) distribution benchmark system. As shown in Fig. 21, the system includes representative sources from all currently important technologies, such as PV, micro-turbines (CHP generation), wind turbines and fuel cells. Only relevant installation locations and sizes of the micro-sources are indicated. The total installed capacity of the micro-sources is set about 2/3 of the maximum load demand of the feeder (~100 kW), to provide the possibility of simulating load management scenario.

Considering a centralized control approach, to support the islanded operation of the microgrid, a fast-responding central storage unit is connected. This may be either a battery inverter, or any other device with sufficiently fast response to undertake the frequency regulation task upon disconnection from the grid (e.g. a flywheel). Autonomous control is also possible by having local storage (e.g. batteries or ultra-capacitors) and suitable controls at individual micro-sources instead of having a central storage unit [36,37].

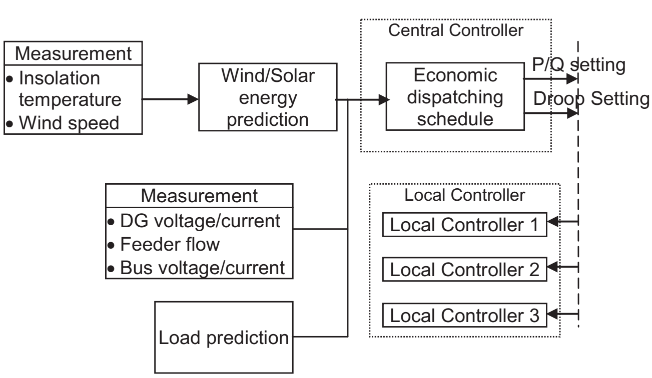

Fig. 18. Two layer control option at the microgrid testbed in Hefei University of Technology.

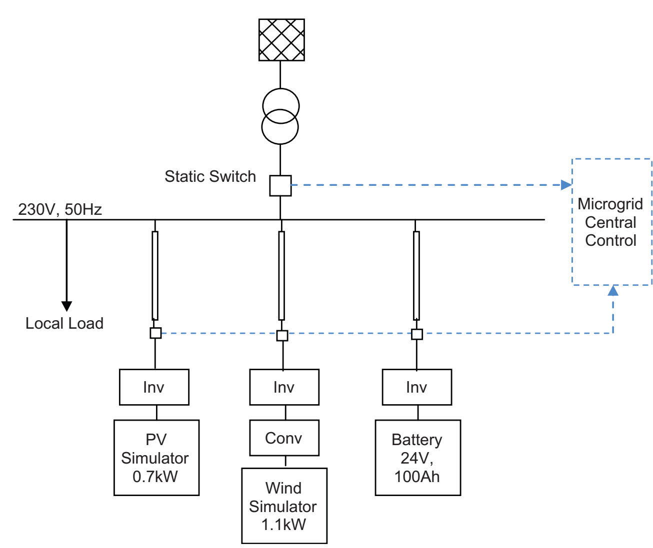

Fig. 19. Laboratory scale microgrid in Hong Kong.

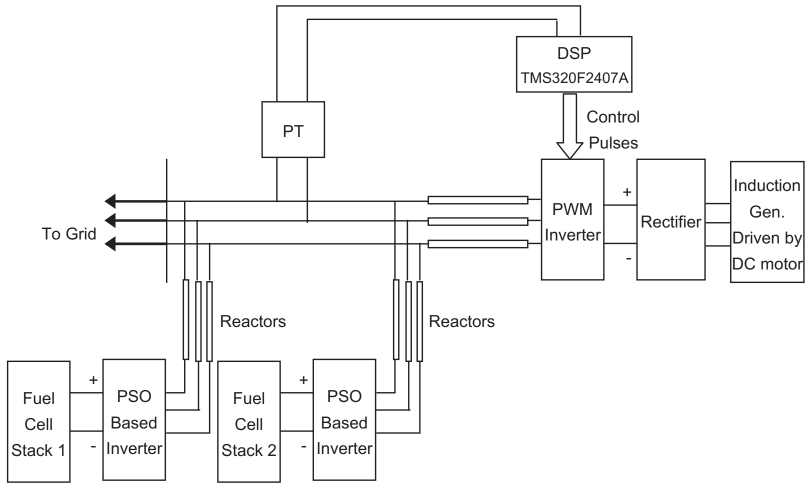

Fig. 20. Test microgrid in India.

3.2.2. Two DG microgrid test network

The system is simulated to study possible control options in a microgrid when considerably large, two synchronous generators are connected. There is no energy storage in the system. Fig. 22 presents the single line diagram of the microgrid simulation model [38].

Different controlling options are studied using this test system:

1. DG1 isochronous mode with DG2 in droop control.
   – DG1 supplies total power until it hits its rating and at further increase of demand DG2 supplies the power depending on droop. Frequency depends on the droop and load frequency characteristics.
2. DG1 in isochronous mode while DG2 in fixed power control mode.
   – DG1 absorbs the load changes until it hits its rating and at further increase of demand microgrid needs to be shutdown unless otherwise DG2 mode of operation is changed.
3. Both DGs in isochronous mode without communication.
   – System collapses as both generators cannot be run at the same speed.
4. Both DGs in isochronous mode with communication.
   – Communication is used to prevent measurement errors thus, to eliminate conflict between the generator governors.

3.2.3. Converter fed microgrid

The microgrid shown in Fig. 23 consists of a collector bus, a bus capacitor, a motor load (three phase, wound rotor machine) and a static load. It is assumed that the load is balanced and that the line impedance between the collector bus and the load is small. The microgrid is connected to the bulk power system through circuit breaker. The VSCs employ high bandwidth current controllers and

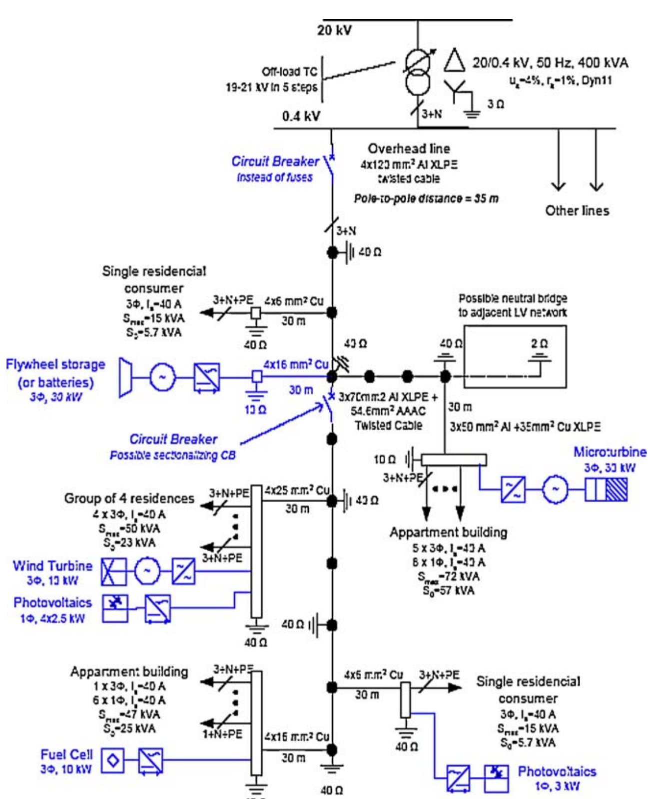

Fig. 21. Benchmark LV microgrid network.

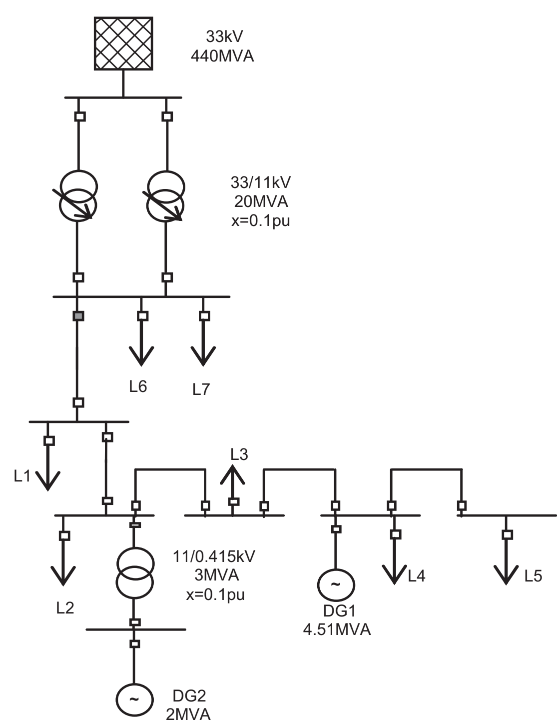

Fig. 22. A two-DG test microgrid without storage.

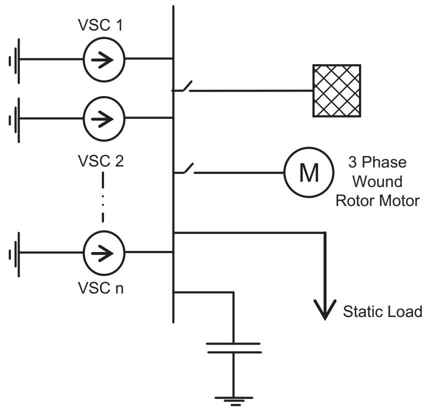

Fig. 23. A microgrid with multiple VSCs.

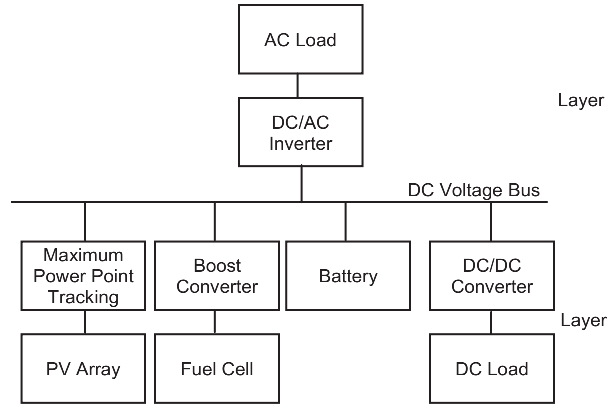

Fig. 24. DC linked microgrid.

consequently, the VSCs together with their interface inductors are modeled as current sources. Converter currents are assumed equal to their current controller reference values [39].

The adopted controlling option is much different to the general controlling methods. The controlling method is named as *voltage-power droop/frequency-reactive power boost (VPD/FQB)* control. This allows current controlled VSCs to operate in parallel under both islanded mode and grid connected mode. Each VSC in the microgrid has its own VPD/FQB controller that sets its current references to regulate the voltage and frequency of a common microgrid bus to track drooped References.

In islanded operation, multiple VSCs with VPD/FQB controls jointly regulate the microgrid voltage and frequency and share a common real and reactive load in proportion to their voltage and frequency droop coefficients. In grid connected operation, the microgrid voltage and frequency are dictated by the bulk power system. Each VSC then delivers real and reactive power as determined by the voltage and frequency references and the droop coefficients of its VPD/FQB controller.

3.2.4. DC linked microgrid

The DC linked microgrid comprises a PV panel, a fuel cell and a battery, which are connected to the same DC voltage bus through appropriate DC–DC power converters and controls, as shown in Fig. 24. The DC load represents the local DC load demand, while the AC load represents the power drawn by the upper level [40].

The approach adapted is hierarchical and power electronic interfaces and controls permit the aggregated units at each level to represent themselves to a higher level as a single self-controlled entity (DC or AC, load or generator).

The controller for the PV subsystem has two modes of operation: maximum power point tracking (MPPT) mode and bus (battery) voltage limit (BVL) mode. The fuel cell operating under nearly steady state conditions, while the battery is responsible for transient energy delivery or recovery by supplying or absorbing instantaneous peak power. Thus, the controller is responsible for managing the fuel cell output current and regulating the bus voltage. A classic PID compensator associated with a PWM generator is selected for fuel cell current control and the fuel cell is turned off when the battery is fully charged.

4. Collective look at the test systems and control options available

In this section, it is attempted to summarize the microgrid test systems and control options that were discussed in the previous section. Table 2 illustrate the use of micro-sources at each microgrid, and types of energy storage used indicating whether it is a central storage, coupled with each micro-source or connected at intermittent DGs and load types used. It also indicates whether the system is radial or meshed. Control method is also indicated as if autonomous, central or agent based. Table 2 allows understanding the different ways of adoption of microgrid technology in different regions as of today.

North American countries are not focused on using renewable energy resources, but rather on maintaining the reliability of power supply. In contrast, European and Asian regions have focused not only on reliability of power supply but also very much on utilizing renewable energy and new power generating technologies in testing the microgrids. Also, Asian region, especially Japan has considered all types of loads, which emphasize their concern on reliability of power supply.

In most of the test cases a central energy storage is used and there are few microgrids where there is no energy storage used. In the cases where there is no energy storage, generator inertia has increased purposely or large capacity generators are already available. Only CERTS microgrid in US has used individual energy storages and few test systems are available where only intermittent sources are coupled with energy storages.

In maintaining the voltage and frequency at desired levels, North American built microgrids have used autonomous control, while Asian countries using central control system other than one microgrid in China using agent based control. Application of both central control and agent based control in microgrids is experimented in Europe. Agent based control systems apply different optimization techniques at the top level for operation planning. Local controls in all control methods (autonomous, central or agent based control) applied in practical microgrid test systems use the well known droop control method. It is observed that using both frequency-active power and voltage-reactive power droops insures the system stability.

Some simulated test systems are similar to existing microgrid test systems, but some systems have researched in different approaches. VSC based microgrid test system presents a contrasting local control approach and DC linked test system presents an approach to control the voltage at each level: at DC bus and AC bus, separately.

It is noted that most of the experiments in microgrid test systems do not indicate the islanding detection method adopted. Some systems use tele-metering after islanding happens and some use transfer trip schemes. But, as previously mentioned, for voltage sensitive loads, the critical clearing time is 50 ms unless otherwise the voltage is maintained above 50% [2]. It indicates the importance of having a fast islanding detection method.

Most common anti-islanding methods (that can be used for islanding detection) available include Rate-of-change-of-frequency

Table 2
Summary of microgrid test systems.

Detail			DGs								Energy storage				Load			Microgrid control		
Region	Microgrid	Radial/ Mesh	PV	Solar thermal	Wind	Fuelcell	CHP	Hydro	Diesel/ Steam/ Gas	Motor driven gen	Central (Cen)/ Individual (Ind)/ with Intermittent source(Int(source))	Battery	Fly wheel	Capacitor	Residential (R)/ Commercial(C)/ Industrial (I)	Static	Motor/ electronic	Central	Autonomous	Agent based
Test-Beds and Intentional Islanding Experience																				
North America	Boston Bar, Canada	Radial	–	–	–	–	–	2	–	–	–	–	–	–	R	–	–		✓	
	Boralex, Canada	Radial	–	–	–	–	–	–	1	–	–	–	–	–	R	–	–		✓	
	CERTS, US	Mesh	–	–	–	–	–	–	3	–	Ind	✓	–	–	–	✓	–		✓	
	UW, US	Radial	1	–	–	–	–	–	1	–	–	–	–	–	–	✓	–		✓	
Europe	Bronsbergen, Netherland	Mesh	108	–	–	–	–	–	–	–	Cen	✓	–	–	R	–	–	✓		
	Am Steinweg, German	Mesh	Several	–	–	–	1	–	–	–	Cen	✓	–	–	R	–	–			✓
	DeMoTec, German	Mesh	1	–	1	–	–	–	1	–	Cen, Int(PV)	✓	–	–	R, C	–	–	✓		
	CESIRICERCA, Italy	Radial	8	1	1	–	2	–	1	–	Cen	✓	✓	–	–	✓	–			✓
	Kythnos, Greece	Radial	7	–	–	–	–	–	1	–	Cen	✓	–	–	R	–	–	✓		
	NTUA, Greece	Radial	2	–	1	–	–	–	–	–	Cen	✓	–	–	–	✓	–			✓
	Uni. of Manchester, UK	Radial	–	–	–	–	–	–	–	1	Cen	–	✓	–	–	✓	–	✓		
Asia	Aichi, Japan	Radial	3	–	–	7	–	–	–	–	Cen	✓	–	–	I, C	–	–	✓		
	Kyoto Eco-Energy, Japan	Mesh	2	–	1	1	–	–	1	–	Cen	✓	–	–	R	–	–	✓		
	Hachinohe, Japan	Radial	5	–	4	–	–	–	3	–	Cen	✓	–	–	I, C	–	–	✓		
	CRIEPI, Japan	Mesh	3	–	–	–	–	–	–	–	–	–	–	–	–	✓	–	✓		
	Sendai, Japan	Radial	1	–	–	1	–	–	2	–	Cen	✓	–	–	R, C, I	–	–	✓		
	HFUT, China	Mesh	2	–	2	1	–	1	1	–	Int(PV), Int(wind)	✓	–	✓	–	✓	✓			✓
	Lab-scale, China	Radial	1	–	1	–	–	–	–	–	Cen	✓	–	–	–	✓	–	✓		
	IET, India	Radial	–	–	–	2	–	–	–	1	–	–	–	–	–	✓	–	✓		
Simulation Studies (Some Significantly Different Cases)																				
Benchmark low voltage microgrid		Radial	2	–	1	1	1	–	–	–	Cen or (Ind)	(✓)	✓	(✓)	R	–	–	✓	(✓)	
2 – DG microgrid		Radial	–	–	–	–	–	–	2	–	–	–	–	–	–	✓	–		✓	
Converter fed microgrid		Radial	Simulated as current sources								–	–	–	–	–	✓	✓		✓	
DC linked microgrid		Radial	1	–	–	1	–	–	–	–	Cen	✓	–	–	R	–	–		✓	

(RoCoF), Voltage Vector Shift (VVS) relays and transfer trip schemes. It is out of scope of this paper to discuss on islanding detection methods. However, it is worth to note the typical response time of the relays: RoCoF relay response time is (3–32 cycles + 5 ms) and response time of VVS relay is (2 cycles + 5 ms) [41]. Also, these relays at their lower settings present generating high level of nuisance tripping signals [42]. Transfer trip schemes are expensive and they become complex with the increased number of DGs.

Beside the voltage sensitive loads, islanding detection time could be a critical factor on microgrid transient stability. Thus, it is important to research in finding the critical time margin to maintain the system stability in a particular microgrid to avoid black starts. Also research in fast and reliable islanding detection methods would serve the purpose of avoiding black starts in microgrids thus, increasing the power system reliability. There found to be new controlling approaches proposed in literature. But, in implementing microgrids, conventional droop control is always used. When it comes to future scenarios the system should allow separations of the controlling in to agents. Thus, it is important to have a microgrid simulation model, which uses widely accepted control options with the provision for future changes. Studying transient stability of a microgrid under different contingencies would help developing the protection schemes. Also, having an accepted simulation model would help the development of microgrid standards.

5. Conclusions

Microgrids are likely to play a key role in the evolution of smart-grids. They could become prototypes for smart-grid sites of the future.

There are many variations in adopting the microgrid architecture and design. However, they are implemented with common perspectives such as reliability and optimal integration of DGs. With the present experience, identifying the dependable control strategies and utilizing them accordingly to further improve the system reliability is a key requirement.

It is important to research in more reliable, fast responding islanding detection method that would be simple in integrating to a microgrid. It is also important to study the critical transition period (from grid connected mode to islanded operation mode) for stable operation of a microgrid. The survey reveals conventional controlling methods are always used in microgrid implementations. Thus, development of a generic simulation model that would reflect the properties of the present microgrids would facilitate further research in transient stability performance, protection and control strategies and development of design guidelines standards for microgrids.

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N.W.A. Lidula received the B.Sc. (Eng.) degree from University of Moratuwa, Sri Lanka, in 2002 and the M.E. degree from the Asian Institute of Technology, Bangkok, Thailand, in 2006. Currently she is pursuing the Ph.D. degree in the Department of Electrical and Computer Engineering at University of Manitoba, Winnipeg, MB, Canada. Her research interests are in distributed and renewable energy systems. She is a graduate student member of IEEE.

A.D. Rajapakse received the B.Sc. (Eng.) degree from the University of Moratuwa, Katubedda, Sri Lanka, in 1990, the M.E. degree from the Asian Institute of Technology, Bangkok, Thailand, in 1993, and the Ph.D. degree from the University of Tokyo, Tokyo, Japan, in 1998. Currently, he is an Assistant Professor at the University of Manitoba, Winnipeg, MB, Canada. His research interests include power system protection, transient simulation of power and power-electronic systems, and distributed and renewable energy systems. Dr. Rajapakse is a Registered Professional Engineer in the province of Manitoba, Canada.